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The Dependence of Capillary Force in Rectangular Channels on Heat Input From Below

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ABSTRACT

The effect of heat flux on the capillary forces in rectangular grooves has been studied. Tests were simultaneously undertaken on grooves of different depths so that the effect of varying the aspect ratio could be examined. It was found that deeper grooves are generally capable of providing larger capillary forces than shallow grooves when no heat is applied. Upon the introduction of a heat flux, grooves of all depths showed a degradation in the net capillary force that could be provided to pull fluid upwards against gravity. Three stages of meniscus retreat were observed corresponding to three ranges of heat input. Experiments showed that shallow channels tend to be less sensitive to heat loads than deeper channels.

INTRODUCTION

In the practical application of heat pipes a major operational limit is possible dryout of the wicking material. In many of today's commercial heat pipes the wick is a groove-type structure, Dunn and Reay (1982). It was found that very little is known about the way in which the capillary forces acting on a fluid inside a small groove change with the introduction of a heat input. It is this capillary force which determines, to a large degree, the way in which the wick will dryout when the fluid in the microlayer is evaporating faster than it can be replenished. It was decided that a better understanding of the variation of capillary forces with increasing heat flux would be instrumental to a complete description of the dryout process. This preliminary experiment also set out to determine how the depth (i.e. aspect ratio) of a rectangular groove affects the capillary force that is imposed on the fluid in the groove. Here we refer to capillary force without trying to separate out the increased drag associated with make-up flow in the channel.

The current investigation uses information that was gained by Stroes et al. (1990) during previous work on dryout of thin fluid films flowing over a flat plate. The general setup of the experimental apparatus, the magnitude of the heat fluxes required and knowledge of which fluids are conducive to wick studies were all deduced from the earlier efforts.

APPARATUS

The heart of the experimental apparatus is a flat copper plate measuring 22.0 cm x 10.5 cm x 0.238 cm. The plate was machined with grooves running in the lengthwise direction. The grooves (or channels) are 1 mm wide and vary from 0.60 mm deep on one side of the plate to 0.95 mm deep on the opposite side of the plate. The grooves are spaced at a pitch of 2 mm. Figure 1 shows an explanation of the positive (upward) and negative (downward) directions which are referred to in this paper. This figure also shows the orientation of the grooves on the plate, and explains the definition of "meniscus height."

During the experiment the plate is tilted at a small angle (3 degrees in this study) and the fluid under investigation is allowed to be pulled up the grooves by capillary action. In order to accomplish this a constant supply of fluid had to be provided at the lower end of the plate. A reservoir was glued to the plate which was capable of holding a small reserve supply. This reservoir was maintained at a constant level by dripping liquid from an Oppenheimer vessel which was suspended above the apparatus. The rate of flow of fluid into the reservoir was constantly monitored using an adjustable valve so that the reservoir would not run dry as the imposed heat flux caused an increased rate of evaporation (fig.2).

It was necessary to obtain very high heat flux capabilities so that the thermal mass of the copper plate could be negated. Ordinary patch heaters were found to be insufficiently powerful, providing a maximum heat flux of only 1.55 W/cm^2 at 115V. A special heating device has been constructed for this experiment which is able to provide heat flux rates as high as 5.6 W/cm^2. The heat is generated through electrical resistivity and the resistive element is a 2 m length of 100 mesh nichrome screen. The screen was cut into a 1.27 cm wide strip which was placed on

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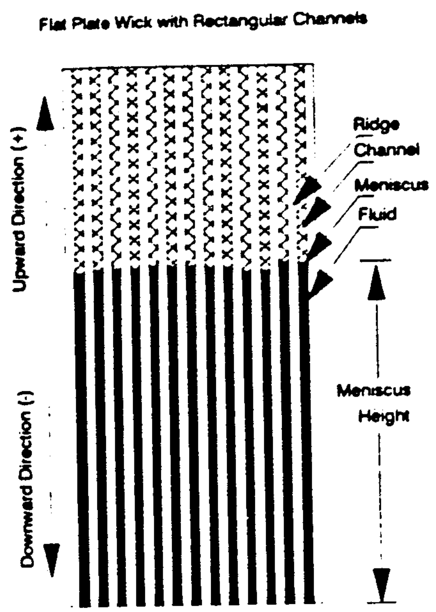

Figure 1. Description of Specific Terminology

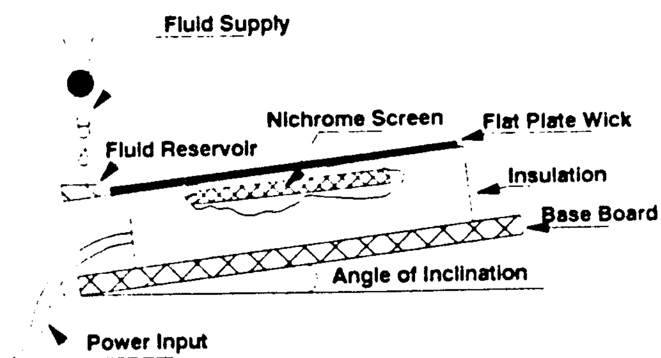

Figure 2. Schematic of Apparatus

edge. It was then bent back and forth into 12 segments each of which is 13.5 cm in length. The screen was fixed so that each segment was within 7.5 mm of the previous segment and none of the segments were in contact (which would cause a short in part of the element leading to a lower resistance value). With this setup a heater was created which was capable of providing a heat flux of up to 5.6 W/cm^2 over an area of 157.5 cm^2.

The heat generated by the nichrome screen was transferred to the grooved plate by radiation. To maximize the transfer rate the heater was placed very close to the underside of the plate (but no closer than 2 mm to avoid any possibility of the screen contacting the copper plate and shorting out). The heater was located beneath the plate in such a way that the fluid meniscus was always above the heated zone. The 13.5 cm long heater was located 2 cm up from the bottom of the plate ... This means that the top 6.5 cm of the grooved plate were ... subject to any heat input, however, in practice the meniscus never climbed high enough for this to be of consequence. The heated zone is 10.2 cm in width and the plate is 10.5 cm wide.

In order to ensure that all of the heat generated by the nichrome strip flowed upwards into the plate, the heating element was insulated on all four sides and on the bottom. Insulation was provided using plaster of Paris ($k = 0.22$ W ...). The thickness of the insulation was 4 cm on the bottom of the heater, 3 cm on the sides of the heater, 2 cm in front of the heater and 6.5 cm behind the heater. The grooved copper plate was set on top of this "block" of plaster and the entire system was mounted on a board whose angle of inclination could be adjusted.

PROCEDURE

The meniscus height (fig.1), defined as the total length of a channel that supports a layer of fluid, is measured as a function of the heat flux through the plate. Measurement of the meniscus height, however, is complicated by difficulties in observing the location at which the thin layer of fluid ends. Without special lighting, a variation in luster can be observed between the wet and dry areas of the grooves, but the transition between the two is not always distinct. In order to overcome this obstacle, a long fluorescent light is mounted approximately 50 cm above the plate, and is oriented such that the bulb is parallel to the meniscus. The reflection of this light off of the fluid dramatically improves the visibility of the transition point between the wet and dry lengths of the channels.

Measurements of the meniscus height are taken by mounting a millimeter scale along the side edge of the plate. A straight wire is then suspended directly above and parallel to the meniscus being measured (fig.3).

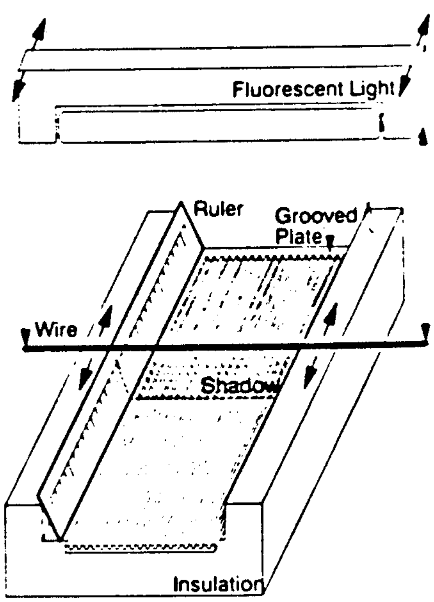

Figure 3. Method of Meniscus Measurement

In order to position the wire directly above the meniscus without disturbing the fluid, it is necessary to adjust the location of both the fluorescent light and the wire such that the plane defined by the length of wire and its shadow intersects the plate perpendicularly. The shadow, which is just the projection of the wire onto the plate, can then be positioned very precisely underneath the meniscus. The position of the meniscus relative to the scale is then determined by measuring the intersection of the scale and the wire.

The fluid used in this study was ethanol, chosen for its low wetting angle and its quick response to variations in heat flux. Each set of measurements starts with the determination of the height that the fluid is drawn up the channels when there is no power being dissipated in the heater and when the plate is at room temperature. The current applied to the heating element is then increased in steps until boiling of the fluid makes the meniscus too chaotic to define. Measurements for each progressive step increase in power are taken after the meniscus reaches an equilibrium level.

RESULTS

Observations show that the net positive capillary force which can pull fluid up a rectangular groove (against gravity) decreases with an increasing heat flux. Figure 4 shows the experimental for all groove depths.

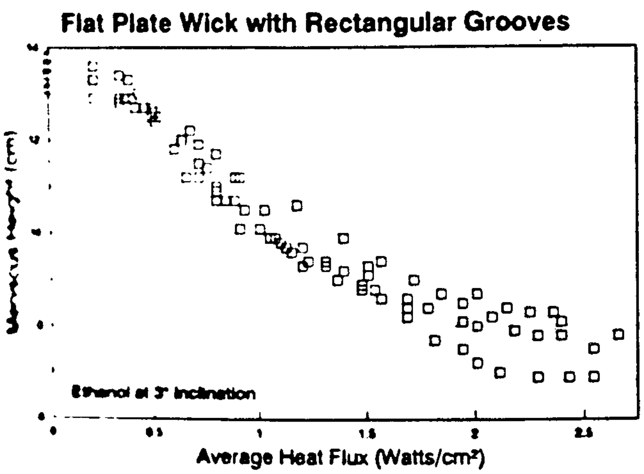

Figure 4. Experimental Data for All Groove Depths

There are several possible causes for this reduction. An increasing heat flux leads to increased evaporation, especially in the micro-layer region near the meniscus. This increase in evaporation requires a larger mass flow rate of make-up fluid. With this increased mass flow rate comes an increased fluid moving through the grooves, and thus a larger drag force in the downward direction (fig.1 describes upward and downward directions.) If this were the only effect, one might expect a linear meniscus retreat with increasing heat flux. The drag force, however, depends on the friction factor, which is not necessarily constant. Ayyaswamy et al. (1974) showed that the friction factor associated with liquid flowing through a (V-shaped) channel depends on the angle at which the surface of the fluid contacts the groove. This contact angle is in turn related to the radius of curvature of the fluid surface.

The radius of curvature of the fluid in the channel may or may not be constant along the length of the groove from the reservoir to the meniscus. If it is constant then the friction factor should be constant as well. However, a high rate of evaporation of fluid from the surface can change the radius of curvature, especially near the meniscus, where evaporation increases dramatically. The high evaporation rate (i.e. mass transfer) produces a momentum recoil effect which can depress the liquid-vapor interface in the micro-layer region producing a reduced radius of curvature (Bankoff,1971). It may be appropriate to assume, therefore, that since the radius of curvature is dynamic, then the friction factor is not constant but dynamic as well and that the subsequent effect on the drag force may not be easily quantified. None the less, the overall effect is that the drag force will increase when a heat flux is introduced and this will tend to push back the meniscus.

The momentum recoil process described above can have effects beyond determining the liquid's contact angle with the groove (and thereby the magnitude of the friction factor). First, since evaporation from the surface near the meniscus pushes the liquid-vapor interface down into the groove thereby decreasing the radius of curvature, the capillary force which pulls fluid up the groove (against gravity) is increased. This will tend to move the fluid farther up the plate. At the same time, though, the momentum recoil exerts a force on the liquid-vapor interface and a component of this force can act to push the fluid down the plate towards the reservoir. Which of these two opposing effects predominates is unknown.

Another force which acts to pull fluid up the plate arises from surface tension where the meniscus contacts the copper. Especially with well-wetting fluids, a large component of the force produced by surface tension is directed upwards away from the reservoir. Since surface tension changes with temperature, this force will also change as the plate is heated. The current investigation makes no attempt to quantify these various effects - here we are only interested in the change of the net upward force that is exerted on the fluid in the channel as it is exposed to an increasing heat load from below.

Regardless of groove depth, menisci were found to retreat in three stages (fig.4). As the heat flux is initially applied there is a reluctance of the triple interface to move from its initial position. In other words, a primary stage exists in which the net upwards capillary force is not much affected by heat input. When the heat flux is increased further stage two is reached. In this region the capillary force is more sensitive to changes in the heat input and the meniscus retreats an appreciable amount when the heat flux is stepped up. Beyond this there is stage three, the nucleate boiling limit. As boiling begins in the micro-layer region the meniscus becomes chaotic and difficult to define. However, it appears that the meniscus position is again less sensitive to increases in the applied heat flux once boiling occurs.

The experimental data shows that during stage one increasing the heat flux by 1 W/cm^2 caused the meniscus to recede approximately 1.5 cm (this is an average value for all the groove depths). Once in stage two, an increase in the heat flux of 1 W/cm^2 caused the meniscus to recede approximately 4.2 cm. And finally in stage three, the nucleate boiling limit, increasing the heat flux by 1 W/cm^2 caused a meniscus retreat of only 0.9 cm (fig.4).

With regard to channel shape, the study revealed that deeper channels consistently provide greater capillary forces then the shallow channels before any heat is applied. However, upon an increase of the heat flux input, the percent change in the meniscus position is greater for deeper grooves (fig.5).

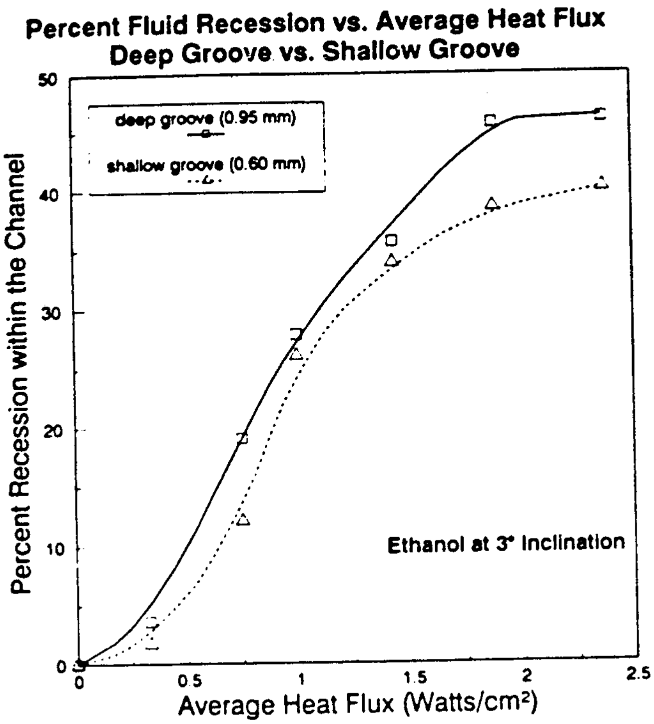

Figure 5. Effect of Groove Depth

Comparing the deepest channels (d=0.95 mm) to the shallowest channels (d=0.60 mm) the following observations were made. During stage one the meniscus in the shallow groove retreats only about half as much as meniscus in the deep groove (measured as a percentage change in the meniscus height relative to the no heat flux condition). In stage two the shallow grooves becomes more responsive, the percentage recession being almost equal to that of the deeper grooves. Once in stage three, the nucleate boiling limit, the meniscus in the shallow grooves falls behind again. At the highest heat flux used during the tests (2.37 W/cm^2) the meniscus in the shallow channel had moved down the plate approximately 86% as far as had the meniscus in the deepest groove (relative to the initial meniscus position). Figure 6 shows experimental data for the meniscus height as a function of both heat flux and channel depth.

CONCLUSIONS

The experimental data shows that the net force which is available to pull fluid up an inclined grooved plate is noticeably affected by a heat input from below. Regardless of the aspect ratio of the channels, the fluid meniscus is observed to retreat down the plate in three distinct stages as the applied heat flux is evenly incremented. Within each stage, however, grooves of varying depths respond differently to heat loads - shallow grooves being less sensitive and deeper grooves being more sensitive to a heat flux from below. It is apparent that capillary forces are not alone in determining how far fluid is pulled up the inclined

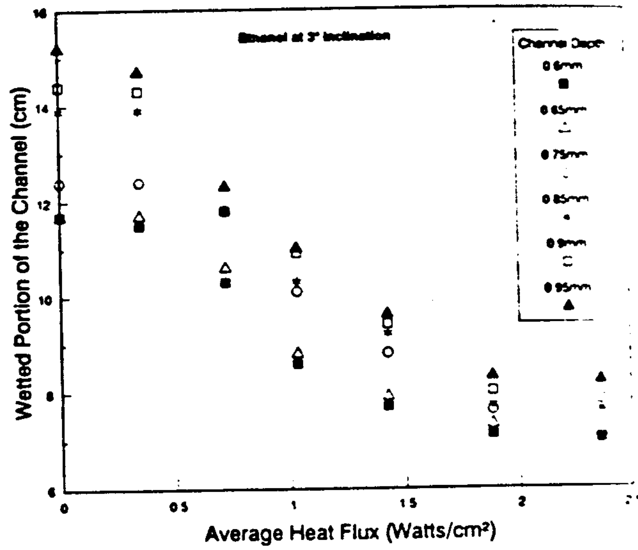

Figure 6. Dependence of Capillary Force on Channel Depth

grooves. In this case, capillary force refers to the pressure difference arising within the liquid due to a varying radius of curvature from one end of the groove to the other. Drag forces within the channels and surface tension forces at the menisci must also be assumed to affect how far liquid moves up the grooves. Furthermore, the momentum recoil produced by the high evaporation rate in the micro-layer region may cause a force which pushes liquid down the incline. Momentum recoil may simultaneously act to increase the radius of curvature near the meniscus, thereby adding to the capillary force which pulls fluid up the incline.

FUTURE WORK

The current experiment was designed to ascertain the basic trends that can be expected when fluid in narrow channels is heated from below. It remains to be discovered what effect groove geometry has on the capillary force. Both triangular and curved grooves are being considered for investigation. A plan has also been made to study fluids other than ethanol - namely Freon TF, methanol and perhaps water. Another factor which deserves attention is the effect that the angle of inclination of the channels has on the meniscus recession process. The current study has used an angle of three degrees but angles as low as one degree and as high ten degrees should also be examined in order to provide a greater range of the component of gravity acting downwards in the channels. Future work will also attempt to quantify the various forces which are involved when a liquid filled groove is heated from below.

It should be noted that this investigation has made no provisions for determining the wall temperature in or around the grooves during the heating process. The extreme temperatures generated by the nichrome heater have made it difficult to mount ordinary thermocouples underneath the copper plate. Several ideas are under consideration to deal with this situation. It may be possible to run thermocouples in from the upper surface of the plate, or special (expensive) high-temperature thermocouples may be employed.

ACKNOWLEDGEMENTS

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